GN&C Technologies for Safe and Precise Landing

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Outline

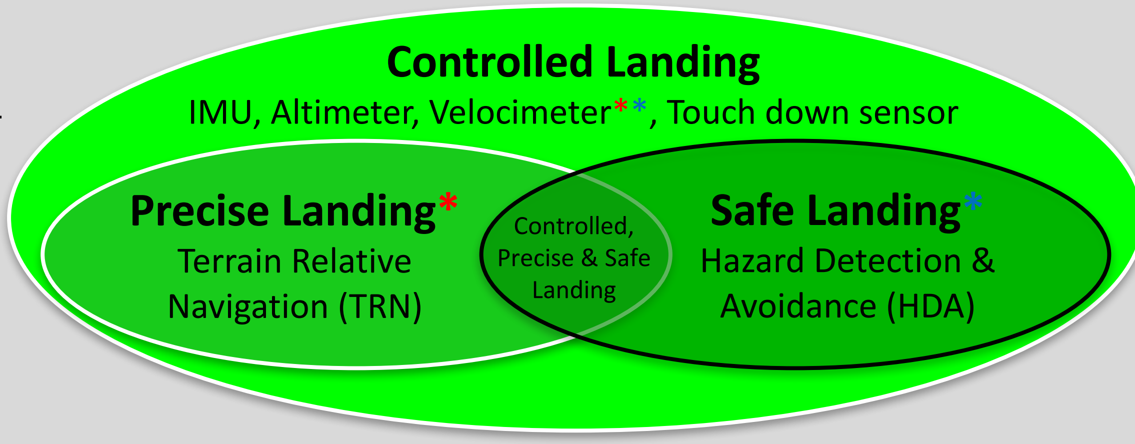
- Precision Landing & Hazard Avoidance ConOps
- ALHAT
  - Hazard Detection and Avoidance
  - Hazard Relative Navigation
- COBALT
  - Terrain Relative Navigation
- Status & Next-Steps

GN&C Lander-System Capabilities Progression

<u>Progression of GN&C Landing-System Capabilities</u>

* Technologies tested with ALHAT

* Technologies being tested with current COBALT payload



Controlled Landing

- Minimize vertical descent rate and lateral velocity to ensure a soft (or controlled) touchdown
- No knowledge of global position – "blind" landing

Precise landing – Terrain Relative Navigation (TRN)

- Global navigation through onboard matching of real-time terrain sensing data with *a priori* reconnaissance data
- Enables efficient maneuvering to minimize landing error and avoid large hazards identified in *a priori* analyses

Safe Landing – Hazard Detection & Avoidance (HDA)

- Real-time terrain sensing to identify sites safe from lander-sized hazards that are undetectable in *a priori* data
- Enables a hazard avoidance maneuver to the identified safe site

Generic **PL&HA** Concept of Operations

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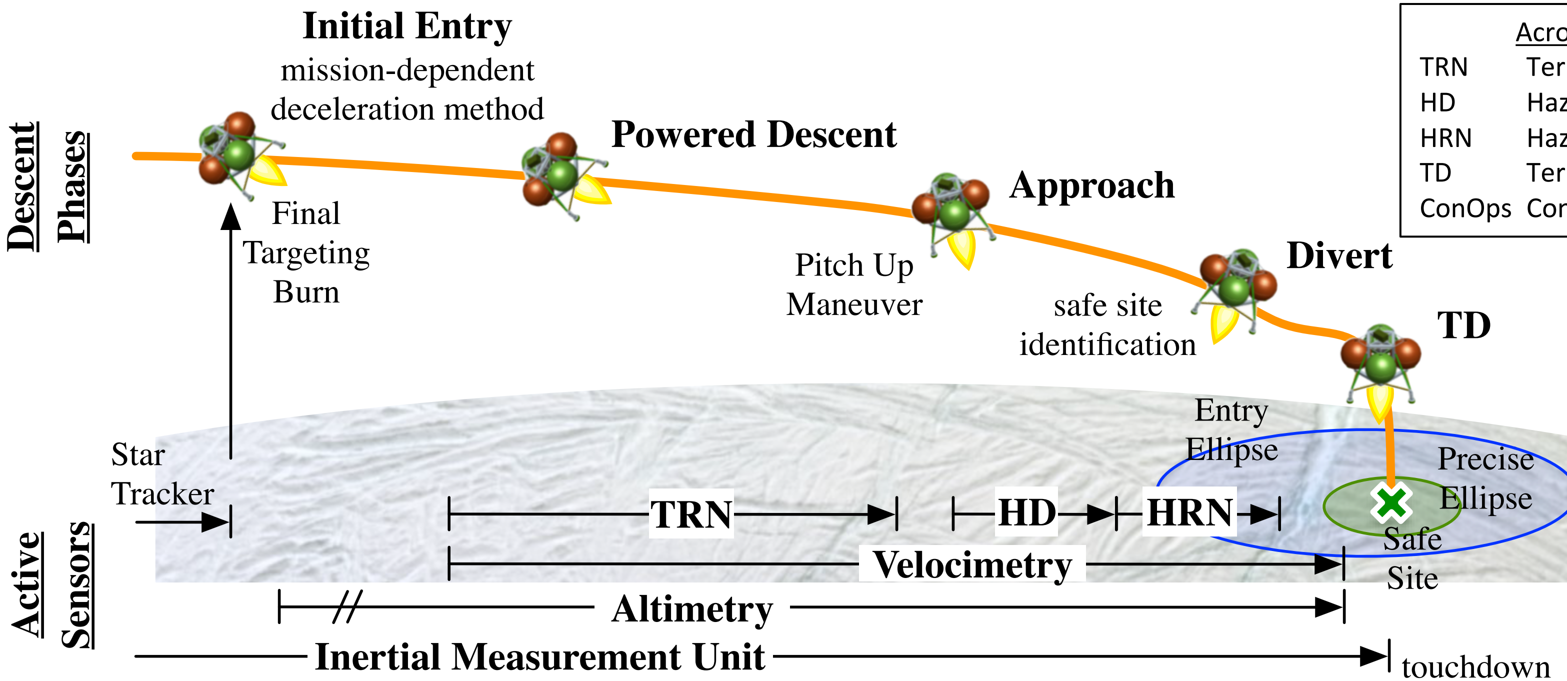
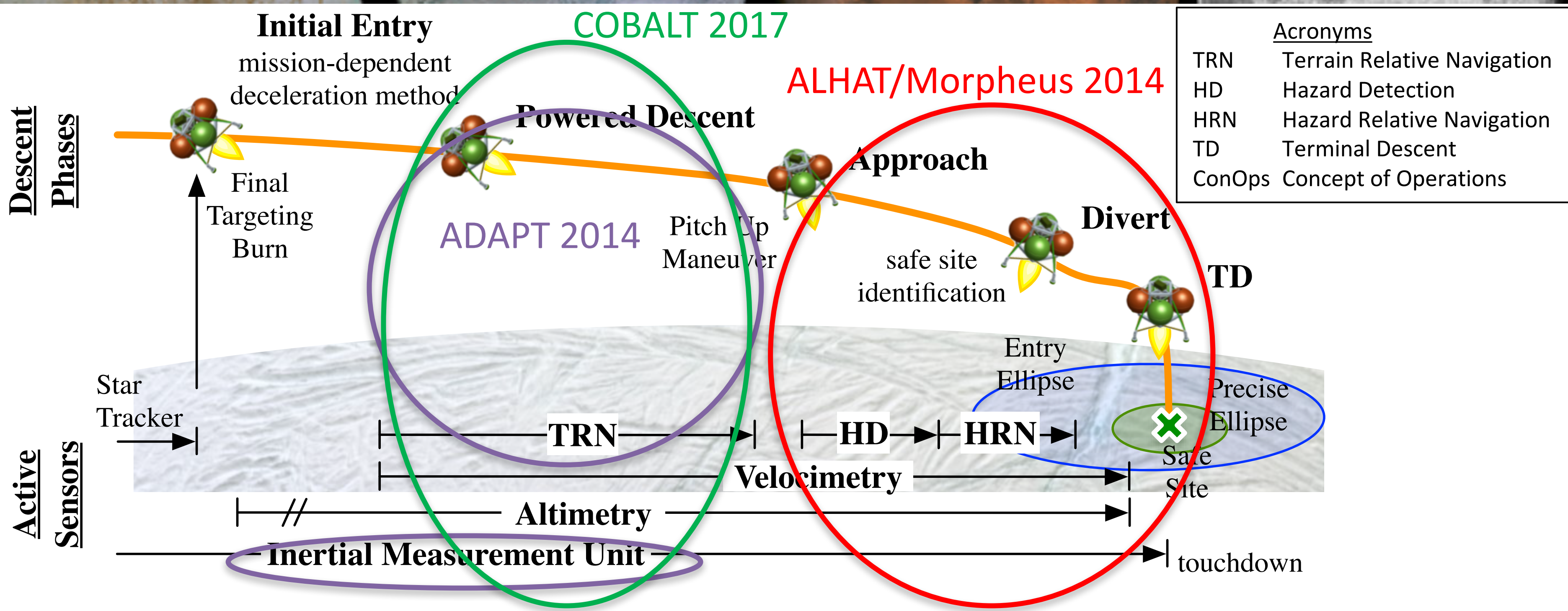


Acronyms	
TRN	Terrain Relative Navigation
HD	Hazard Detection
HRN	Hazard Relative Navigation
TD	Terminal Descent
ConOps	Concept of Operations

- Mission landing needs and risk posture define which PL&HA capabilities to utilize
- TRN: Perform TRN and measure altitude & velocity as early as possible to determine global position and for use in landing error reduction
- Velocimetry during or toward the end of TRN minimizes subsequent navigation position error growth prior to HD/HRN and during TD
- Dead reckon on IMU for TD to mitigate dust effects to other sensors

ALHAT & COBALT Regimes



- COBALT blends LVS TRN with NDL Velocimetry and Ranging
- Tests a PL&HA ConOps segment not demonstrated with ALHAT/Morpheus or ADAPT/Xombie
- Higher altitude and descent rate than either Morpheus or Xombie

ALHAT Overview

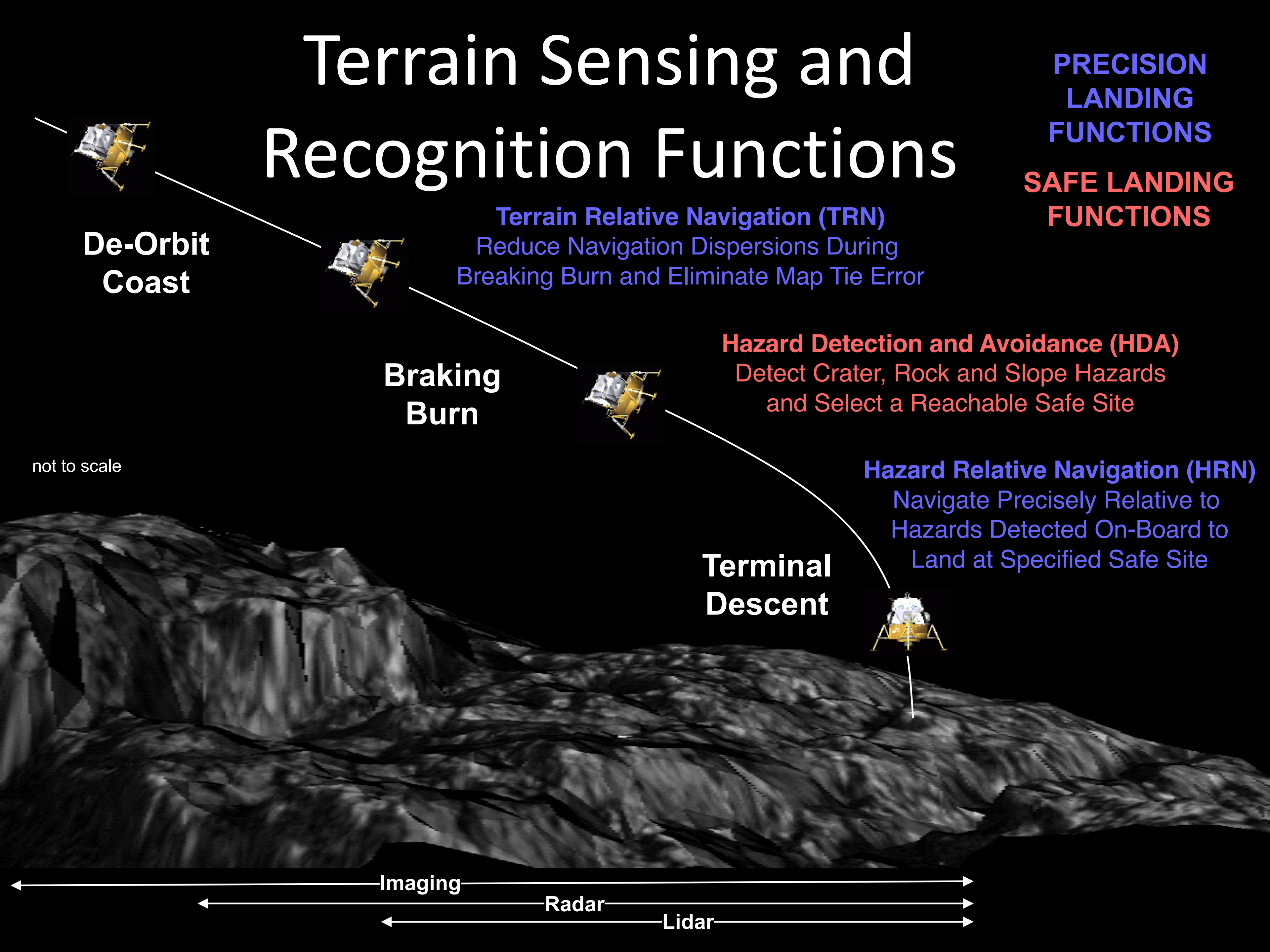
Autonomous **L**anding **H**azard **A**voidance **T**echnology

- ALHAT combined autonomous guidance, navigation and control algorithms capable of characterizing the landing surface while identifying and avoiding lander-sized hazards in real time
- ALHAT flew on JSC's Morpheus Lander as a self-contained payload with the goal of prototyping future hazard avoidance & hazard relative navigation systems for future robotic or human landers on the moon

Johnson Space Center
Houston, Texas

Langley Research Center
Hampton, Virginia

Jet Propulsion Laboratory
California Institute of Technology


Terrain Sensing and Recognition Functions
PRECISION LANDING FUNCTIONS
SAFE LANDING FUNCTIONS
De-Orbit Coast
Terrain Relative Navigation (TRN)
Reduce Navigation Dispersions During Breaking Burn and Eliminate Map Tie Error
Braking Burn
Hazard Detection and Avoidance (HDA)
Detect Crater, Rock and Slope Hazards and Select a Reachable Safe Site
not to scale
Hazard Relative Navigation (HRN)
Navigate Precisely Relative to Hazards Detected On-Board to Land at Specified Safe Site
Terminal Descent
Imaging
Radar
Lidar

Hazard Detection and Avoidance (HDA) overview

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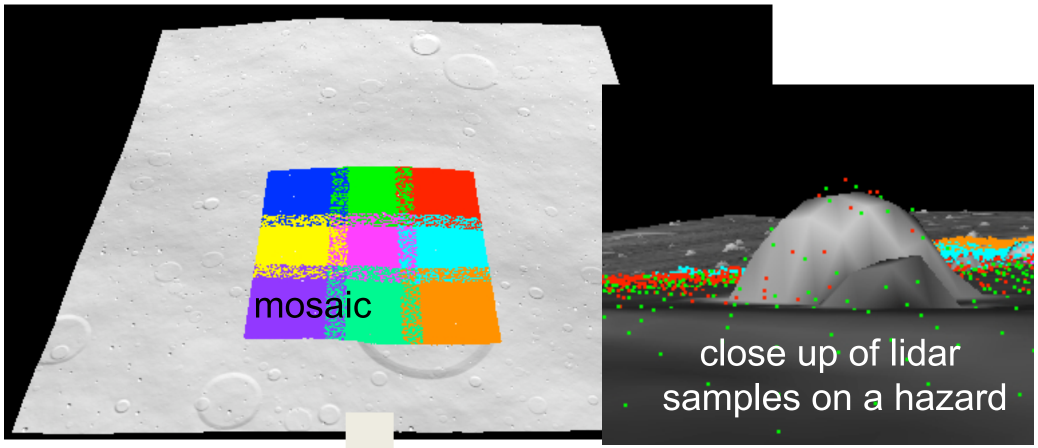
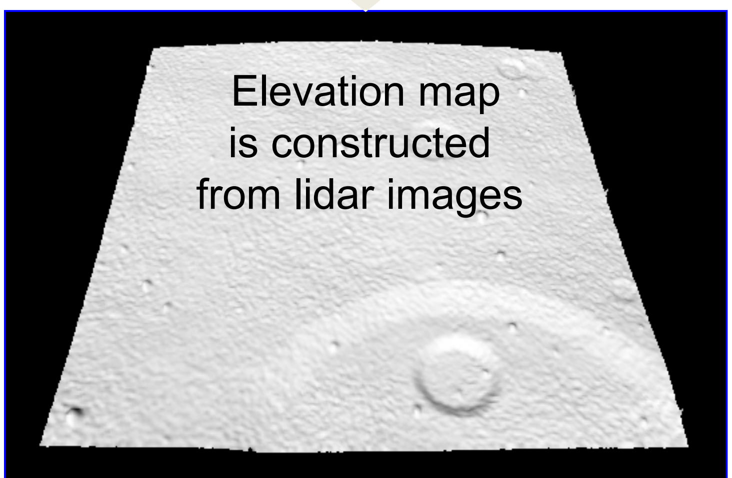
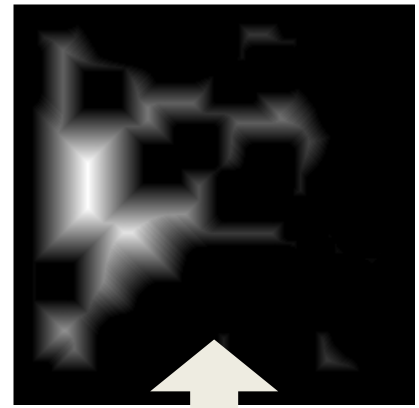
Mosaic of LIDAR images generated using gimbal as spacecraft descends

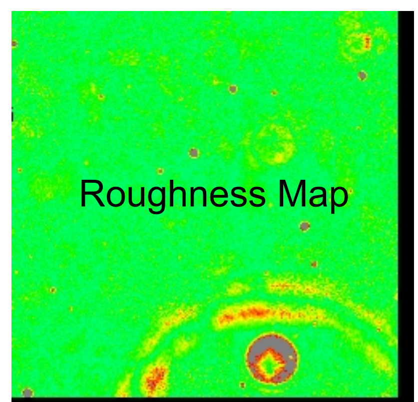


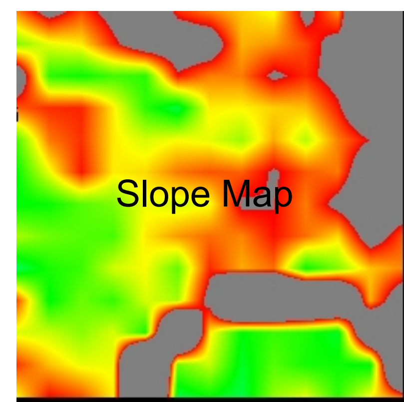


Safety map sent to Host Vehicle for selection of safe and reachable site



HDA algorithm detects slope and roughness hazards and computes safety map





Hazard Relative Navigation (HRN) overview

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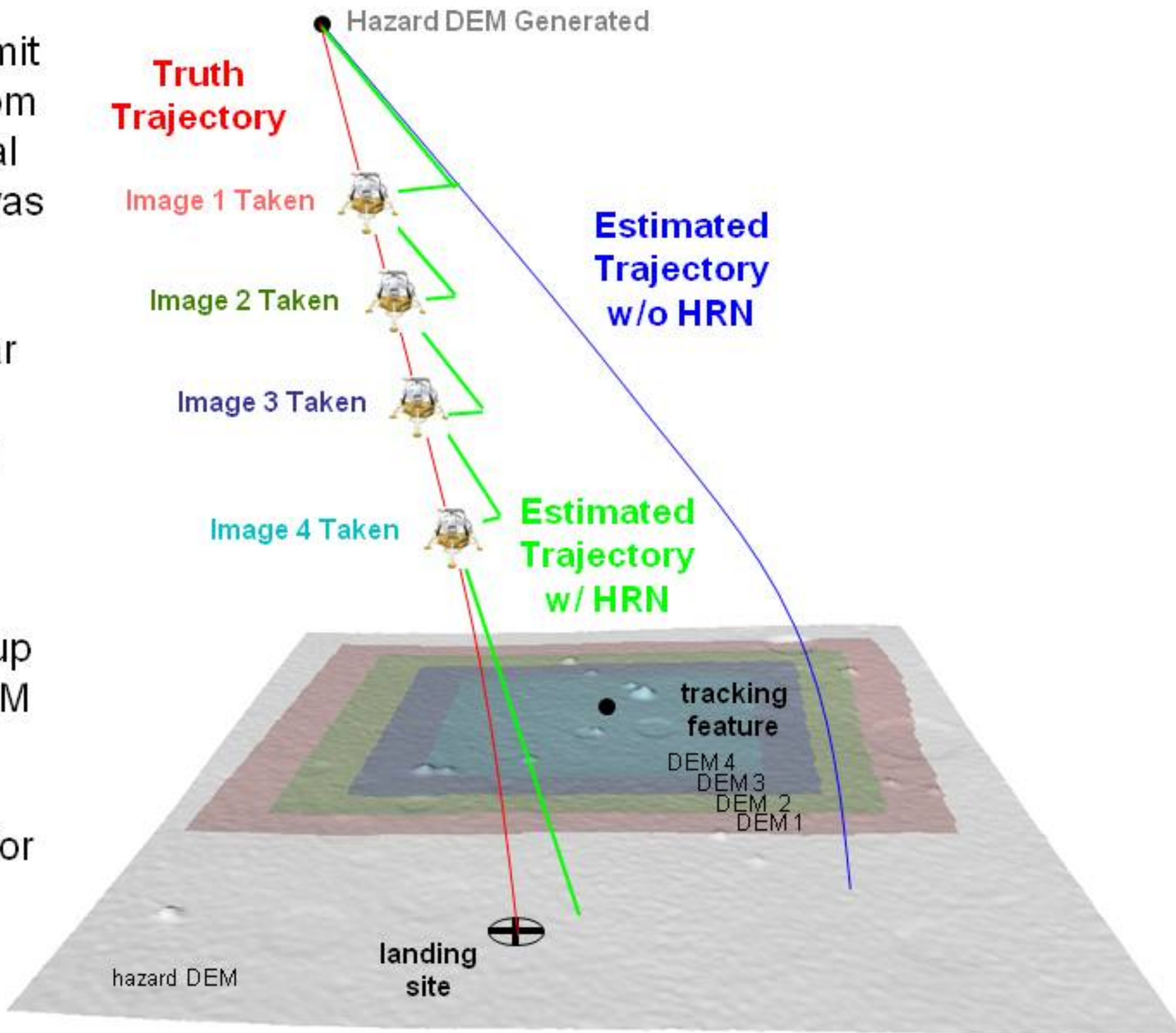
Purpose of HRN is to limit position error growth from time when hazard Digital Elevation Map (DEM) was constructed.

As lander descends lidar images are taken and turned into DEMs using current state estimate.

Any position error in current state will show up as a shift between HDEM and current lidar DEM.

Position shift is solved for using DEM correlation.



HDS Compute Element (HDSCE) Hardware Overview

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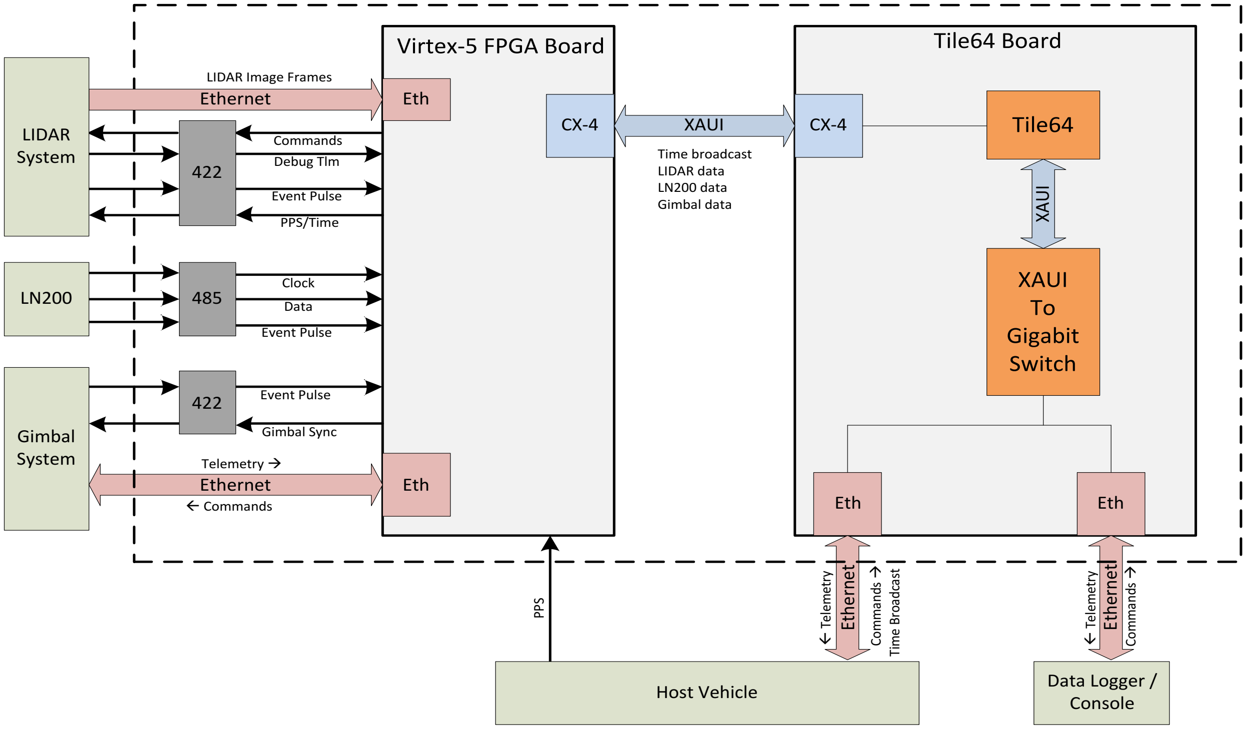
HDS Compute Element (Tile64 Board Configuration)



Overall HDSCE Block Diagram and interface with external devices

Major HDSCE Components:

- FPGA board for I/O integration and system timing
- TILE64 Single Board Computer for processing/host vehicle interfacing

HDS Software

- Combination of multi-process, multi-threaded and parallel elements that communicate with each other via POSIX message queues
- Heavy computation elements utilize the Tilera parallelization and communication API
- All other elements use standard UNIX APIs
- Isolating Tilera specific APIs to only the heavy computation elements means only few developers need learn non-standard APIs, and allows other components to be developed and debugged on any POSIX compliant O/S
- Sensor time labeling offloaded to external FPGA to alleviate real-time requirements on software

HDS-CE Software

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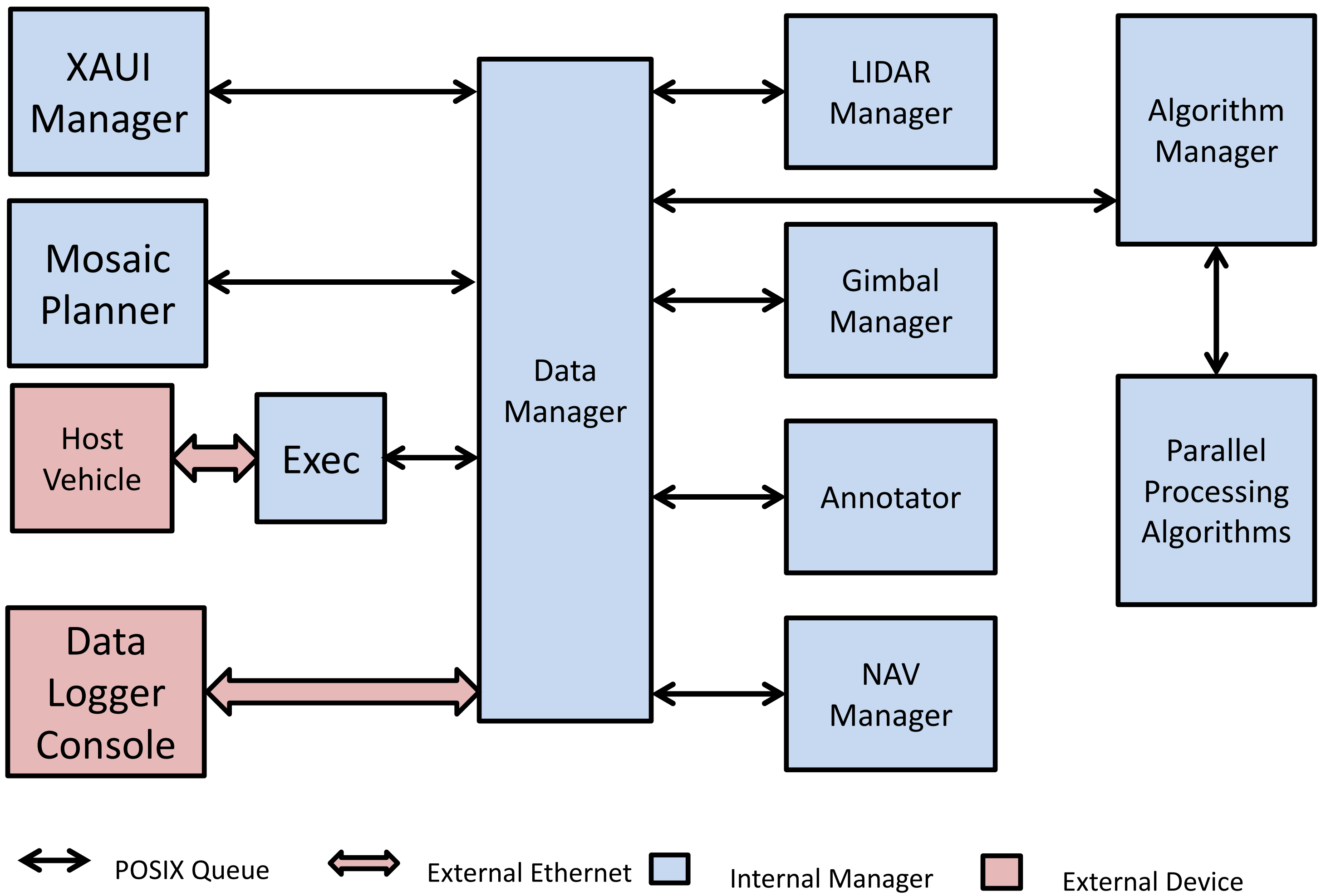

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HDSCE Software Components - 1

- **Algorithm Manager:** Single threaded, highly responsive thread that queues up data products and commands for Algorithms. Allows Algorithms to be CPU bound and not miss data/commands.
- **Parallel Processing Algorithms** —The "Heavy lifter" CPU intensive processing element. This component is Tilera specific parallel. Handles all HDA, HRN, and feature tracking.
- **Annotator** – Annotates each incoming range image with an integrated pose relating sensor and map coordinate systems valid at the time the flash was taken
- **Data Manager** – The central data routing resource. All messages pass through data manager and are distributed on a pre-compiled subscription list. Also contains the logging/replay interface to the system.
- **HDS Executive** – The overall manager/commander of the HDSCE. Triggers tasks on each manager depending on the current mode. Interfaces with host vehicle.

HDSCE Software Components - 2

- **Gimbal Manager/Mosaic Planner** – Interfaces to and manages the gimbal. Integrates current vehicle and NAV state to accurately point or slew the gimbal according to the current mode (vehicle relative pointing, ground relative pointing, ground relative mosaic)
- **LIDAR Manager** – Interfaces to and manages the attached LIDAR instrument. Commands the LIDAR, assembles range images from LIDAR data, etc.
- **NAV Manager** – Propagates HDS NAV state from integration of host vehicle and HDS IMU measurements based on current HDS mode. Broadcasts computed NAV state to HDS subcomponents.
- **XAUI Manager** – Manages the interface between the FPGA and processor via the 10Gb/s XAUI link. Uses Tilera specific APIs to ensure low latency and high bandwidth.

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ALHAT Technology Advancement

ALHAT flight tests onboard the Morpheus Lander demonstrated:

- Fully automated, high-precision, perception-based, real-time system for safe landings
- Use of LIDAR sensors, applicable for day or night landings
- Ability to reconstruct terrain with high-fidelity at sub-meter resolution
- Lander-scale surface characterization of terrain features: terrain effective slope and terrain effective full roughness
- Lander-geometry based slope and roughness hazard assessment for terrain safety probability estimation
- Incorporated sensor noise and navigation uncertainty into safety assessment and safe landing sites selection

COBALT Overview

Co**O**perative **B**lending of
Autonomous **L**anding **T**echnologies

- A platform to mature TRL and reduce risk for spaceflight infusion of GN&C PL&HA technologies into near-term robotic and future human missions
- Self contained and could be modified to test different GN&C technologies on different platforms

Johnson Space Center
Houston, Texas

Langley Research Center
Hampton, Virginia

Jet Propulsion Laboratory
California Institute of Technology

ConOps for **COBALT**/Xodiac Flights

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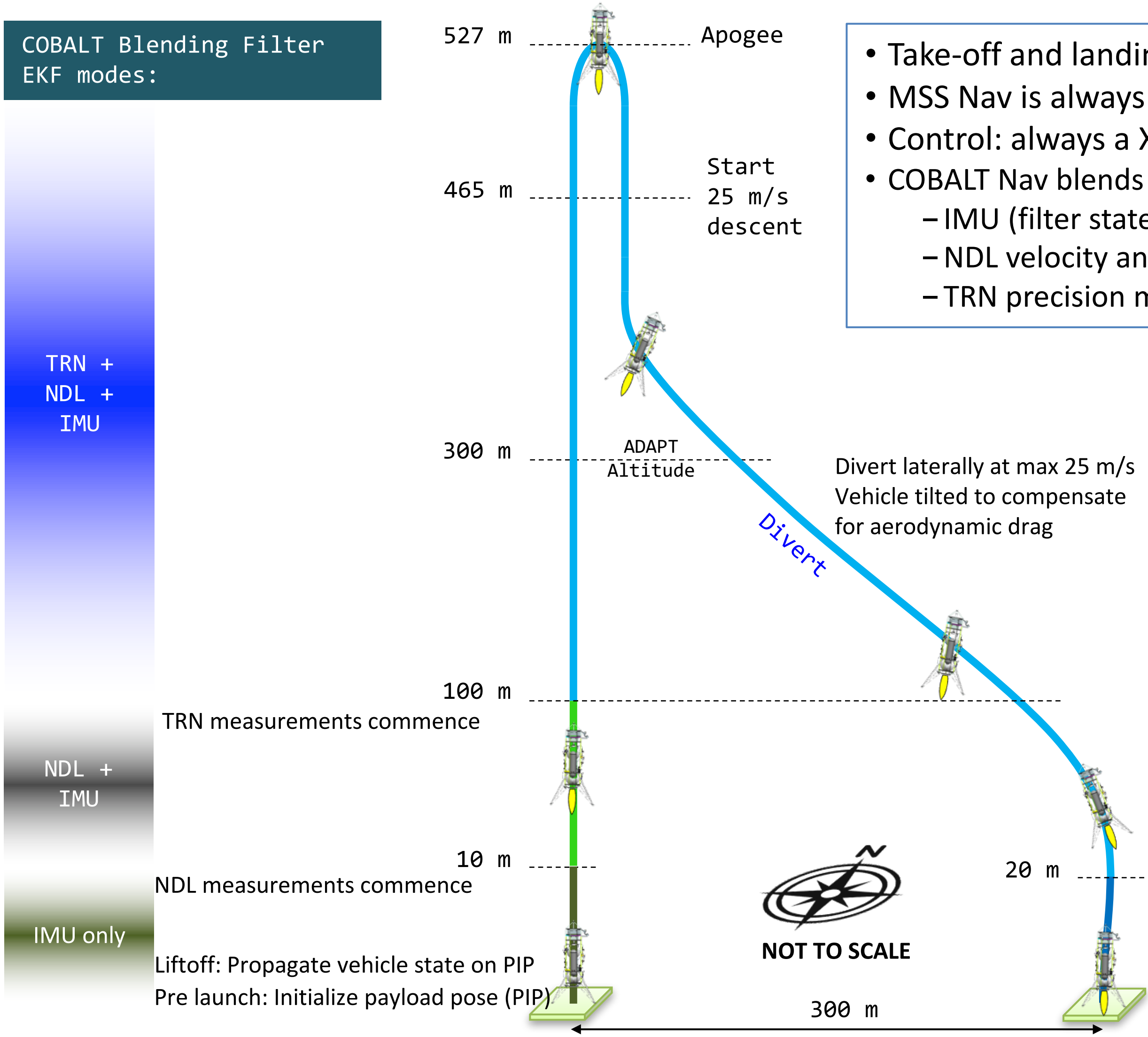
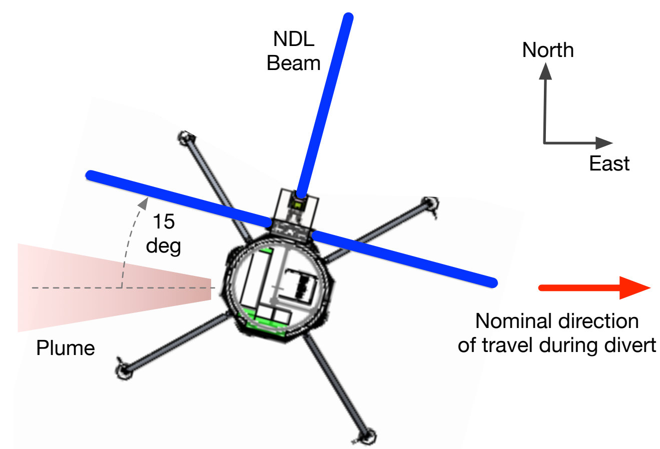
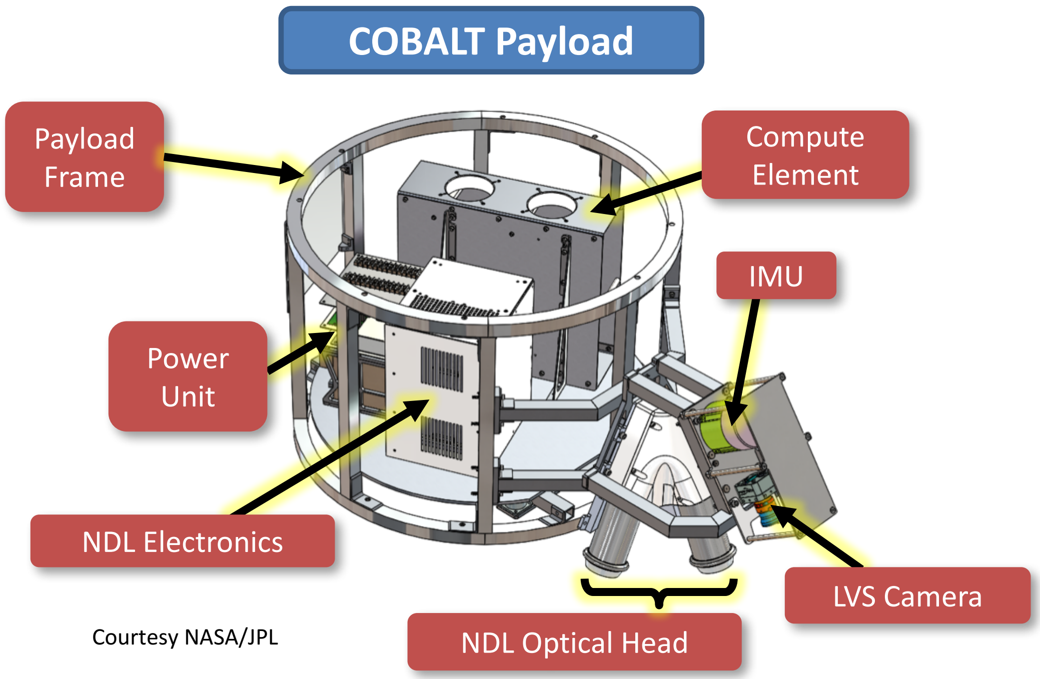
- Take-off and landing sequences always utilize MSS GN&C
- MSS Nav is always online (fallback/watchdog for closed loop)
- Control: always a Xodiac vehicle function
- COBALT Nav blends sensors:
  - IMU (filter state initialized with PIP)
  - NDL velocity and range (> 5-10 m)
  - TRN precision match measurements (> 100 m)



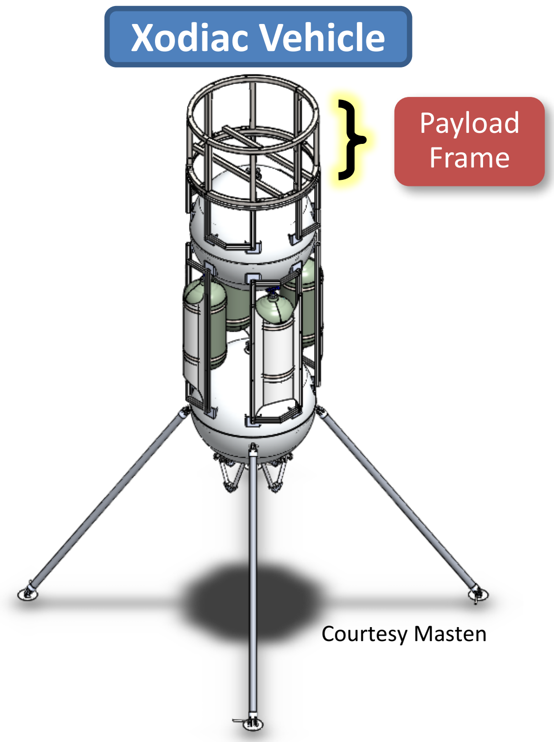


COBALT Payload

- Generation-3 Navigation Doppler Lidar (NDL) for velocity & range measurements
- Lander Visions System (LVS) for Terrain Relative Navigation (TRN) position estimates
- Custom compute element, power unit, and LN200-3 IMU
- Payload frame to mate onto MSS Xodiac vehicle



Courtesy NASA/JPL



Courtesy Masten

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Navigation Doppler Lidar

Velocimetry and Ranging

Langley Research Center
Hampton, Virginia

- The NDL utilizes one seed laser, an optical head(s), photoreceiver(s), plus other custom boards & components (C&DH, synthesizer, fiber amplifier, etc.)
- The NDL Gen 2 flew on Morpheus and had lower maximum velocity and range measurement capabilities
  - Morpheus flight tests reached an altitude of about 250 meters and velocities of 15 m/s
- COBALT is maturing the NDL Gen3 to a TRL 5
  - COBALT flight tests reached an altitude of approximately 500 meters and max speed of 25 m/s
- Follow-on project plans to expand the envelope with further flight tests

Generation 2
(flown on Morpheus in 2014)

Courtesy NASA-LaRC

- Increase max velocity from 75 m/s to 200 m/s
- Increase max range from 3 km to 4+ km
- Reduce size and mass by 40%

Generation 3
(completed Dec 2, 2016)

Courtesy NASA-LaRC / David C. Bowman

Size comparison of
Gen-2 and Gen-3

Courtesy NASA-LaRC

Lander Vision System

Terrain Relative Navigation

- Utilizes one passive-optical camera, an IMU, a dedicated processor, and a reconnaissance map
- Calculates global position based on comparison of camera images to an *a priori* map stored onboard
- Implementation for Mars2020 conducts coarse feature matching to remove large, initial position uncertainty, followed by fine feature matching to obtain precision global position
- COBALT ConOps enables going straight into fine match mode (coarse match not necessary)

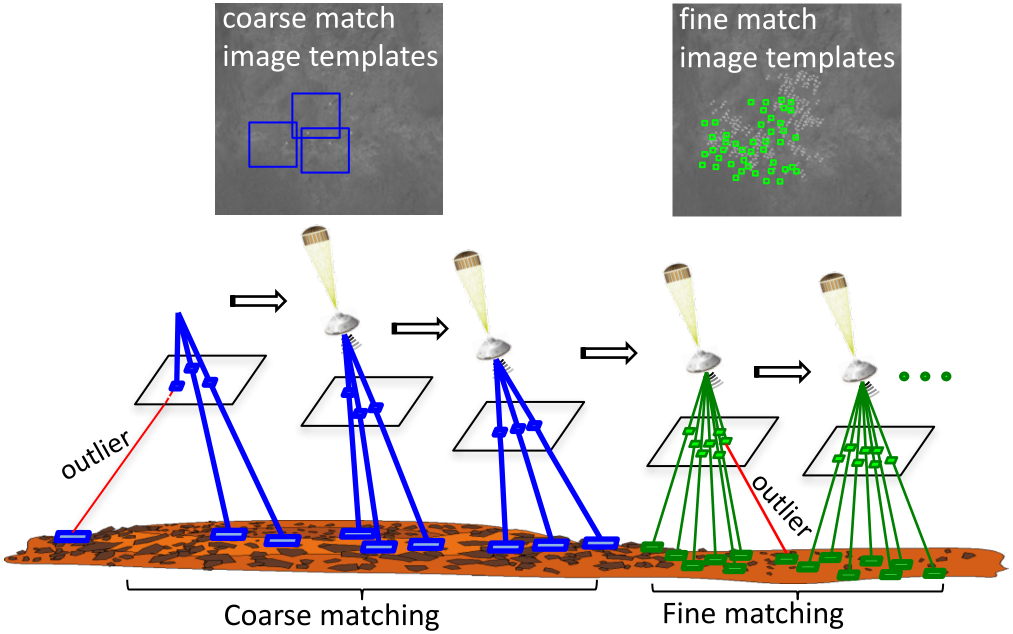
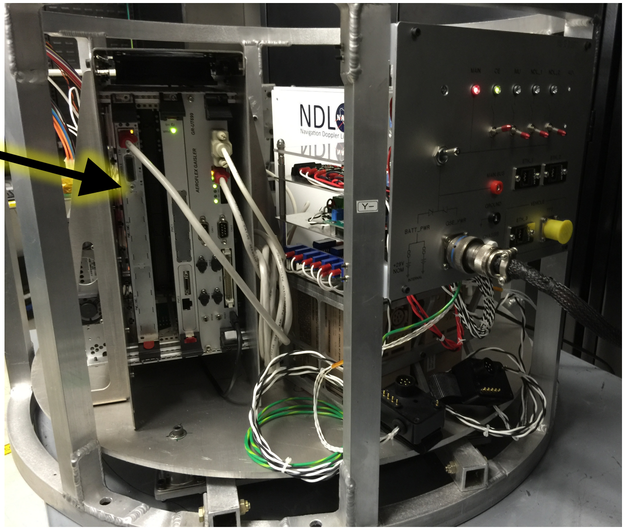


Illustration Courtesy NASA/JPL

Compute Element

- Leverages past architecture from the 2014 ADAPT project
- 5-slot, 6U compactPCI unit
  - Aeroflex LEON3 compactPCI board
  - Virtex-5 FPGA
  - X86-based SBC
- Provides multiple functions
  - Data collection and logging
  - Data processing: TRN images, initial pose, navigation filter
  - Time stamping and time management
  - Communication and telemetry
  - Vehicle interfacing



Courtesy NASA/JPL

COBALT Technology Advancement

Flight tests onboard the Xodiac vehicle demonstrated:

- Successful performance of the Navigation Doppler LIDAR at higher altitudes and faster speeds than previously flown on Morpheus
- Navigation Filter processing of IMU measurements, TRN images for position updates, and NDL velocity measurements

Status & Next Steps

- Hazard Detection & Avoidance, Hazard Relative Navigation
  - ALHAT still state of the art
- Terrain Relative Navigation
  - JPL's Lander Vision System is state of the art
  - Currently baseline for Mars 2020
- COBALT payload
  - March 2017: Integration & tethered flight tests onboard Xodiac rocket
  - April 2017: 2 Free flights onboard Xodiac rocket (COBALT Free Flight)
  - July-August 2017: Two more free flights planned

- Next Steps
  - Mature NDL TRL level from 5 to 6
  - Test NDL at higher altitudes and velocities
  - Develop plan for blending TRN and HDS/HRN

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Questions?

The multiple individuals and organizations supporting COBALT

JSC
- John M. Carson: COBALT Project Lead
- Ed Robertson: PL&HA Domain Lead

LaRC
- Farzin Amzajerdian: NDL Lead
- Glenn Hines: NDL Chief Engineer, NDL C&DH Designer
- Diego Pierrottet: NDL Systems Engineer & Electronics
- Bruce Barnes: NDL Systems Integration
- Jordan Davis: C&DH Board Design & Test
- Larry Petway: NDL Fiber Optic System
- Becky Stavely: NDL Thermal Engineer
- Walter Bruce: NDL Thermal Engineer
- Glenn Farnsworth: NDL Lab Engineer
- Tak-Kwong Ng: NDL FPGA Engineer
- Angela Welters: C&DH Hardware and Firmware
- Vince Cruz: NDL Electronics

JPL
- Carl Seubert: COBALT Payload & Flight Test Lead
- Chuck Bergh: Mechanical, Electrical & Thermal Lead
- Carlos Villalpando: Software/Avionics Lead
- Steven Collins: COBALT Nav Filter Design
- Ara Kourchians: Electrical Engineering
- John Koehler: Senior Technician
- Matt Shekels: Mechanical Designer
- Brent Tweddle: PIP Developer
- Nikolas Trawny: COBALT Technical Support (ADAPT & LVS)

MSS
- Travis O'Neal: Project Technical Lead
- Jeff Gibson: Avionics / GN&C Support
- Nathan O'Konek: Director of Business Ops
- Reuben Garcia: Director of Technical Ops
- Jason Hopkins: Business Manager
- Joey Oberholtzer: Avionics and GN&C support
- Ben Dagang: Propulsion
- Richard Stelling: Xodiac Pilot / GN&C Lead
- Scott Nietfeld: Prior Xodiac Pilot / GN&C Lead
- Kyle Nyberg: Prior Xodiac Crew Chief / Test Conductor

HQ
- Joe Hernandez (AFRC): FO Program, Campaign Manager
- Chris Baker: FO Program, Prior Campaign Manager
- Nantel Suzuki: AES Lander Technologies Program
- Michelle Munk: STMD EDL Principle Technologist
- Wade May: STMD:GCD Program Element Manager

MSFC
- Greg Chavers: PM, AES Lander Technologies Project

Backup

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Why we are doing this?

- Develop precision landing capabilities applicable to future NASA Science and Human missions: COBALT has joint funding from HEOMD-AES and STMD-GCD/FO
- Provide full implementation of integrated hardware and measurement fusion of NDL velocity/range and LVS TRN sensors with direct application to Mars and Moon precision navigation
- Operate NDL and LVS within flight profiles closer to Mars descent conditions: significantly higher altitudes and descent velocities than achieved with Morpheus or ADAPT/Xombie
- Test the ALHAT TRN+NDL closed-loop operational segment that was not achievable onboard Morpheus 1.5B with its current engine
- Implement and demonstrate NDL as a viable velocimeter for future NASA landers:
  - The MSL Terminal Descent System (TDS) is high cost/size/mass/power, has parts obsolescence, and is not practical for small robotic-class missions (e.g., Discovery and New Frontiers)
  - COTS alternative discontinued: Mars Insight uses a flight spare from Mars Phoenix